SuFEx - A selectively triggered chemistry for fast, efficient and equimolar polymer-polymer coupling reactions

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Abstract

The synergy between controlled radical polymerization methods and click chemistry enables the design of complex and well-defined materials. To date, a number of highly efficient reactions have been reported suitable to couple polymers in equimolar amounts within minutes, although such reactions typically require high reactivity, and the active groups are not fully compatible with the conditions applied in radical polymerization, necessitating additional modification steps. Here, we demonstrate how the Sulfur(VI) Fluoride Exchange (SuFEx) reaction proves to be an efficient coupling reaction whilst avoiding the traditional issues encountered in other ligation reactions. Two chain transfer agents (CTAs) for RAFT polymerizations were created, which bear the required orthogonal groups for the SuFEx reaction. Both CTAs yield well-defined polymers, with no observable side reactions, even when both CTAs are utilised in the same polymerization. The choice of catalyst for this click reaction is an important consideration in order to allow efficient polymer coupling using equimolar amounts. Besides the previously reported strong bases, we discovered that salt tetrabutylammonium fluoride (TBAF) is an excellent catalyst yielding almost quantitative

conversions within minutes for different polymers and solvents. This combination of orthogonality towards radical processes and high reactivity is unprecedented in literature.

Introduction

Efficient and selective chemical syntheses enable materials scientists to design an abundant variety of structures for applications ranging from engineering to biomedicine. In particular, special attention has been given to the development of new, versatile and high yielding reactions.[1-8] One cornerstone of this field is the introduction of so-called "click" reactions,[9] with the copper catalysed azide-alkyne cycloaddition (CuAAC) reported by Sharpless *et al*. being the gold standard for these type of reactions.[10] Subsequent investigations let to a variety of other reactions, which fulfil the criteria for click reactions, including for example thiol-ene or Diels-Alder reactions.[3, 4] The special requirements of macromolecular chemistry have led polymer scientist to alter and expand the original definition of a click reaction.[11] A key element is that the reaction should work at equimolarity, a prerequisite when trying to link two polymer chains to avoid complicated purification processes to remove unreacted polymers.[12,13] Only a small number of reactions exhibit most of the characteristics of an ideal click reaction in polymer chemistry. For instance, the hetero Diels-Alder reaction (HDA) permits linking of polymeric chains bearing a dithiocarbonate and an electron-rich diene as chain ends, respectively, and elegantly makes use of the chain transfer end group used in reversible addition-fragmentation chain transfer polymerization (RAFT).[14-16] Other efficient reactions often additionally involve reactive heterocycles undergoing cycloadditions such as the recently reported triazolinedione chemistry or tetrazole-based reactions.[17, 18] Although the reactions mentioned above work highly efficiently in various conditions, they employ reactive groups that are not truly orthogonal to a radical process, and may react with radical species and/or the vinyl groups of the monomers. Consequently, these functional groups have to be introduced post-polymerisation which usually entails additional purification steps, limiting the ability to work at equimolar conditions.[13, 19]

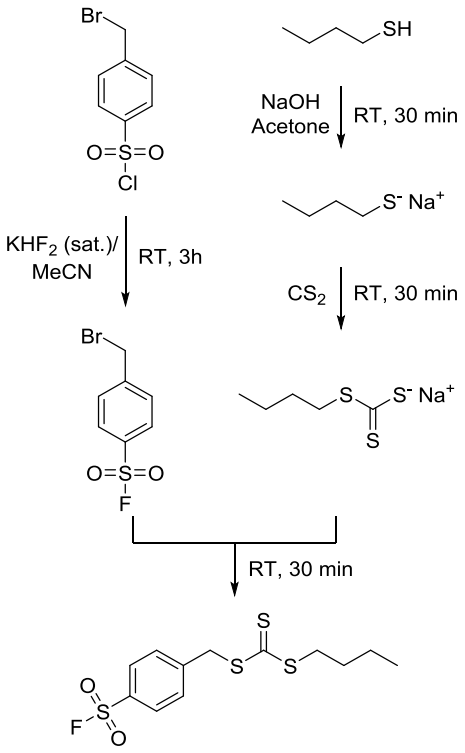
The recently reported Sulfur(VI) Fluoride Exchange (SuFEx) reaction represents a promising candidate to overcome this obstacle as both reactive groups are stable towards radicals, and do not participate in reactions with vinyl groups.[20] This "click" reaction has already demonstrated its potential in polycondensations,[21] side chain modifications,[22, 23] and site specific binding for bioapplications.[24, 25] Despite these beneficial properties and the selectivity of the reactive moieties, its application towards efficient polymer-polymer coupling has not yet been reported. To address this, we designed two suitable chain transfer agents (CTAs) bearing the respective functionalities for SuFEx and tested them in RAFT polymerizations as model radical processes.[26] To demonstrate the stability of the SuFEx

functional end-groups towards radical polymerisation, the respective CTAs were combined in one polymerisation and the resulting homopolymers bearing the complementary end-groups were subsequently tested for coupling. Additionally, several catalysts were assessed for the SuFEx polymer-polymer coupling reaction and their kinetics were monitored. Finally, separate crude batches of RAFT polymers were combined and coupled at equimolar conditions to generate block copolymers, without any need for purification.

Results and discussion

RAFT is a versatile and robust reversible deactivation radical polymerisation (RDRP) method, and may be mediated by a wide variety of chain transfer agents.[27-30] Depending on the type of monomer, the R-group has tremendous influence on the chain initiation.[31-33] Based on known CTAs we designed a simple trithiocarbonate compound which affords excellent control over the polymerization of acrylate, acrylamido, and styrenic type monomers bearing the desired sulfonyl fluoride moiety on its R-group (**Scheme 1**).

Scheme 1. Synthesis of 4-(fluorosulfonyl)benzyl butyl trithiocarbonate (FSBBTC)

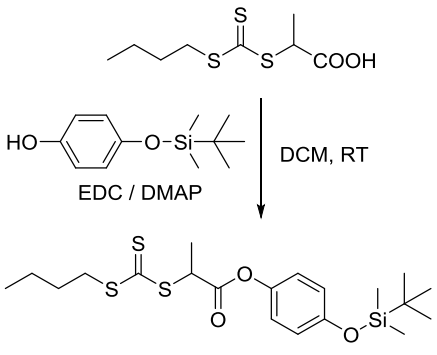


The sulfonyl fluoride starting material (4-(Bromomethyl)benzene-1-sulfonyl fluoride) is obtained in quantitative yields from the reaction of 4-(Bromomethyl)benzene-1-sulfonyl

chloride and potassium bifluoride (KHF_2).[20] Notably, during our work this compound became commercially available, thus enabling easy preparation of the desired CTA in a one-step procedure. The final substitution of the bromine group gave an almost pure product (purity > 95% from NMR, Figure S1) after a few washing steps (see experimental section), which could easily be purified by column chromatography (NMR in Figure S2).

The second CTA bearing the complementary silane-protected alcohol required for an efficient SuFEx reaction was obtained through modification of the previously reported CTA 2-propionic acidyl butyl trithiocarbonate (PABTC) *via* esterification of the carboxylic acid group with 4-(*tert*-Butyldimethylsiloxy)phenol (TBDMSPh) (**Scheme 2**).[34] Both CTAs are stable and do not show any sign of degradation when stored at 5 °C for months (NMRs in Figure S3 and S4).

Scheme 2. Synthesis of 4-((tert-butyldimethylsilyl)oxy)phenyl 2-(((butylthio)carbonothioyl)thio)-propanoate (TBDMSPh-PABTC)



Whilst CTAs based on PABTC have frequently been used in RAFT polymerizations, FSBBTC is to our knowledge unreported. Therefore we first studied the kinetics of a polymerization using 4-Acrylomorpholine (NAM) in 1,4-Dioxane targeting a degree of polymerization (DP) of 40. The monomer was chosen in accordance with our previous studies and due to its excellent solubility in a large variety of solvents including water (**Figure 1**).[35-38]

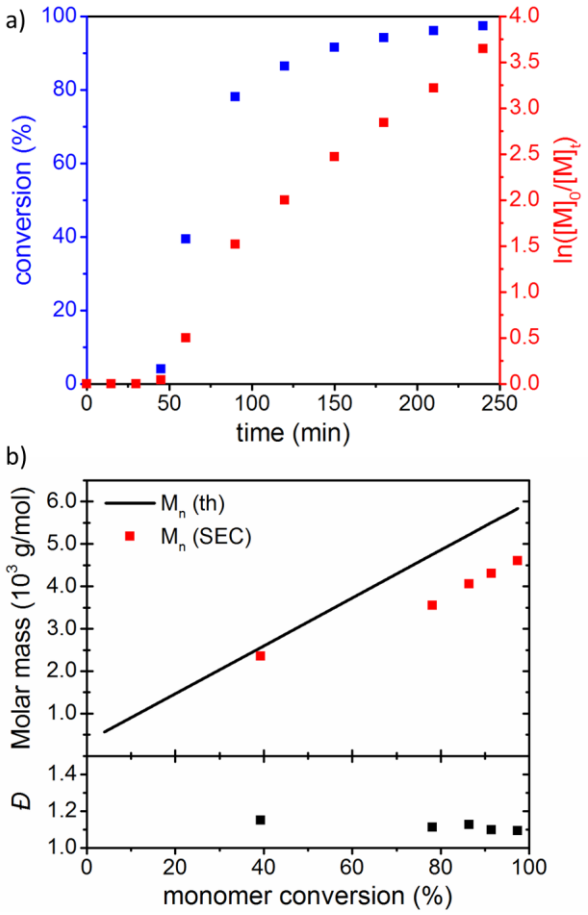


Figure 1. Kinetic plots of the polymerization of NAM using FSBBTC as CTA.

Following an induction period (40 min), most likely due to the low reactivity of the R group, the plot of ($\ln([M]_0/[M]_t$ *vs*. time) exhibits pseudo-first order kinetics typical in RAFT polymerization. In addition, size exclusion chromatography (SEC) in DMF reveals a linear evolution of molar mass with monomer conversion. The deviation of M_n (SEC) from the theoretical values is related to the calibration of the SEC with poly(methyl methacrylate) (PMMA) narrow standards. Nonetheless, the molar mass distribution ($Đ$) remains below 1.2 indicating an excellent control of the polymerization with this CTA, while reaching a high conversion of 97 %. The versatility of the CTA towards different monomer families was examined with the polymerization of an acrylamide (NAM), styrene (S), acrylate (*tert*-butyl acrylate, *t*-BA), and finally a methacrylate (methyl methacrylate, MMA) (**Figure 2**).

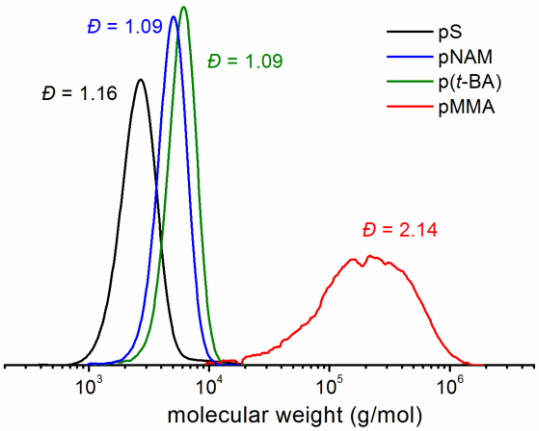


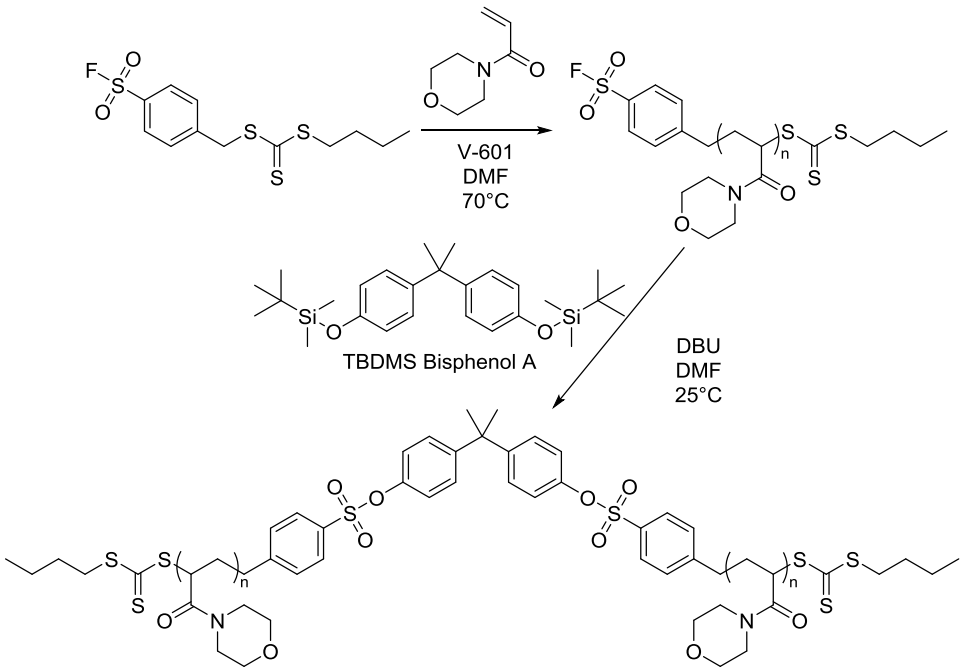
Figure 2. DMF-SEC traces of pS, pNAM, p(*t*-BA) and pMMA polymerized with FSBBTC as CTA.

The polymerizations of styrene and *t*-BA gave narrowly distributed polymers using similar conditions as for the pNAM. However, a broad distribution is observed in the case of MMA, which is most probably related to a low transfer constant of the CTA in this polymerization, as expected from a trithiocarbonate bearing a benzyl leaving radical as R group. Therefore, methacrylates are not considered for further tests as a quantitative incorporation of the CTA cannot be guaranteed.

- Test of end-group reactivity and stability

As previously reported the coupling of two homopolymers using a bifunctional linker is a good methodology to demonstrate and quantify the reactivity of the active end-group. Accordingly we tested the reactivity of our $pNAM_{40}$-SO_2F polymer with a bifunctional silane-protected alcohol linker (**Scheme 3**) and followed the coupling reaction using size exclusion chromatography (SEC). ((propane-2,2-diylbis(4,1-phenylene))bis(oxy))bis(tert-butyldimethylsilane) (TBDMS Bisphenol A) was prepared by silylation of Bisphenol A.[21] The reaction conditions were adapted from the previously published polycondensation reactions using 1,8-Diazabicycloundec-7-ene (DBU) as a catalyst.[21]

Scheme 3. Synthesis of $pNAM_{40}$-SO_2F and coupling reaction using the bifunctional linker TBDMS Bisphenol A and DBU as catalyst



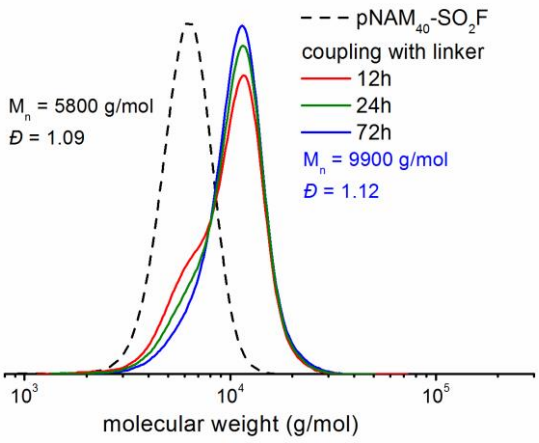


Figure 3. DMF-SEC traces of the homocoupling of $pNAM_{40}$-SO_2F using a bifunctional linker (TBDMS Bisphenol A) and 0.3 eq. of DBU as catalyst.

Following 12 h of coupling using DBU (0.3 equivalents) as catalyst a new major population is observed in the DMF-SEC at higher molar mass which can be attributed to the coupled polymers, with only a small lower molar mass population corresponding to the precursor polymer remaining (**Figure 3**, details are given in Table S1). Within 72 h almost complete coupling is observed. The coupling efficiency was determined from the number distribution plot to be 96 % (Figure S5).[13, 19] The result verifies the preservation of the sulfonyl fluoride end-group during RAFT polymerization and its high reactivity for the SuFEx reaction. We

have to mention that, despite the good match of the deconvoluted traces, the accuracy at very high values for conversion might suffer from an overrepresentation of lower molar mass fractions, which is related to the large impact of the baseline correction converting the plots into the number distribution, and a limited match of the Gaussian fit to the real distribution. Despite these limitations, this analysis still allows the quantification of the coupling efficiency and does not only rely on a qualitative comparison of the SEC traces.[39]

As silylation of an alcohol is a common method for protection and similar silanes have been used in RAFT polymerization, TBDMSPh-PABTC was not studied in detail. However, combining both complementary CTAs under typical RAFT conditions (65 °C, concentration of CTA ~ 0.1 M) could potentially lead to undesired side reactions and/or uncontrolled coupling. To assess this we performed the polymerization of NAM (targeted DP of 40) in the presence of both CTAs (50/50 mixture).

DMF-SEC of the resulting polymer(s) exhibited a monomodal distribution (**Figure 4**, dashed black line) with no evidence of polymer-polymer coupling, since a similar molar mass (M_n = 5100 g/mol) is obtained compared to the pNAM$_{40}$-SO$_2$F prepared previously (M_n = 4600 g/mol). Furthermore, both CTAs seem to possess similar reactivity and transfer constants as no low molar mass tailing is observed which would indicate insufficient transfer or reinitiation. However, this result does not prove the preservation of the active chain ends for the SuFEx reaction. Therefore we examined the resulting solution by NMR spectroscopy (Figure S6). The aromatic signals for both end-groups remained unchanged in comparison to the polymers prepared with the individual CTAs and no additional signals in this region appear which would indicate the presence of side reactions. Although this result is promising, the accuracy of NMR spectroscopy of polymer solutions has certain limitations. Adding both CTAs in equimolar amounts allows us to assess the full activity of the chain ends through attempting the coupling reaction. In this first test the coupling conditions as mentioned above (RT, in DMF, 0.3 eq. DBU as catalyst) were used (**Scheme 4**).

Scheme 4. Polymerisation using a 1/1 ratio of the CTAs FSBBTC and TBDMSPh-PABTC and the subsequent coupling of the resulting polymers using DBU as catalyst.

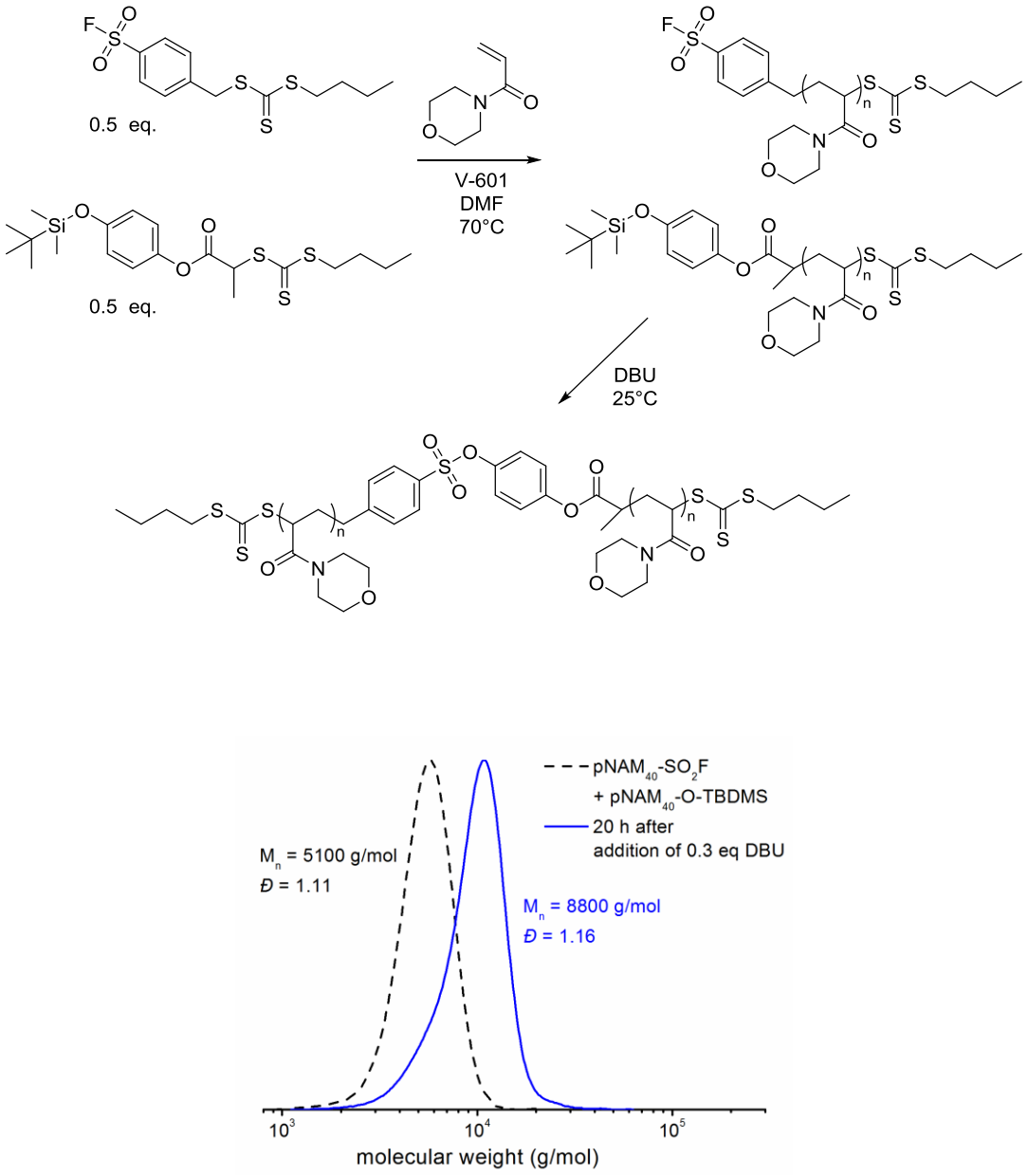


Figure 4. Normalized DMF-SEC traces of the precursor mixture (dashed) and the final coupling after 20 h (solid) of pNAM-SO_2F and pNAM-O-TBDMS using 0.3 eq. DBU as catalyst.

The SEC revealed an efficient coupling reaction of the polymer chains, (**Figure 4**, details are given in Table S1) which is indicated by the clear shift in the SEC trace. The conversion was determined by the deconvolution of the final SEC trace and gave a coupling efficiency of 93 % (deconvolution of number distribution plot is given in the SI, Figure S7). As mentioned previously, the accuracy of the deconvolution might be limited at such high conversions, but the obtained values are in the same range as for polymer-polymer coupling reactions using the highly efficient CuAAC.[40] Therefore, we assume that such a high efficiency could only be

obtained if all end-groups are still present and reactive. From this we can conclude both functional groups are stable to typical RAFT conditions and the coupling reaction is instigated only by the addition of a suitable catalyst. High conversions are obtained even at room temperature and without requiring the usual precautions to exclude oxygen or water impurities.

- Influence of catalyst

Previous publications on SuFEx reactions have already reported the significant influence of the catalyst employed.[21-23] Various compounds were examined, mainly comprising strong bases such as DBU, 1,3,5-Triazabicyclo[4.4.0]dec-5-ene (TBD) or 2-*tert*-Butylimino-2-diethylamino-1,3-dimethylperhydro-1,3,2-diazaphosphorine (BEMP). A suggested mechanism involves the reaction of these catalysts with the sulfonyl fluoride to form an activated sulfonamide salt including the released fluoride as counterion.[41] This ion subsequently reacts with the silane group and the released alcoholate replaces the nitrogen on the sulfur of the sulfonyl group to form the stable sulfonate link. Recent studies on fluorinating reagents support this possibility, although the real mechanism has still to be investigated.[42] Notably, soluble fluoride salts such as CsF can also catalyse the reaction, which cannot occur according to the presented mechanism due to the missing activated sulfonamide species.[21] An issue with the use of CsF in organic solvents is its limited solubility which coincides with a low ion dissociation in these media, therefore it was not considered in our experiments.

Based on these previous studies we decided to examine a variety of catalysts including the reported DBU and TBD, but also 7-Methyl-1,5,7-triazabicyclo[4.4.0]dec-5-ene (MTBD) which is less nucleophilic than TBD. In addition we tested tetrabutyl ammonium fluoride (TBAF) which has so far been overlooked as an alternative to the hardly-soluble CsF. Commonly used for cleavage of silane protection groups, TBAF displays an excellent solubility in various organic solvents including THF or 1,4-Dioxane.[43] The activity of the catalysts was studied in similar coupling reactions as mentioned above for the test with DBU. For all reactions 0.3 equivalents (with respect to the active end-groups of the polymers) of catalyst were added to start the coupling reaction. Samples were taken at various time points

to study the kinetics of the reaction using DMF-SEC (

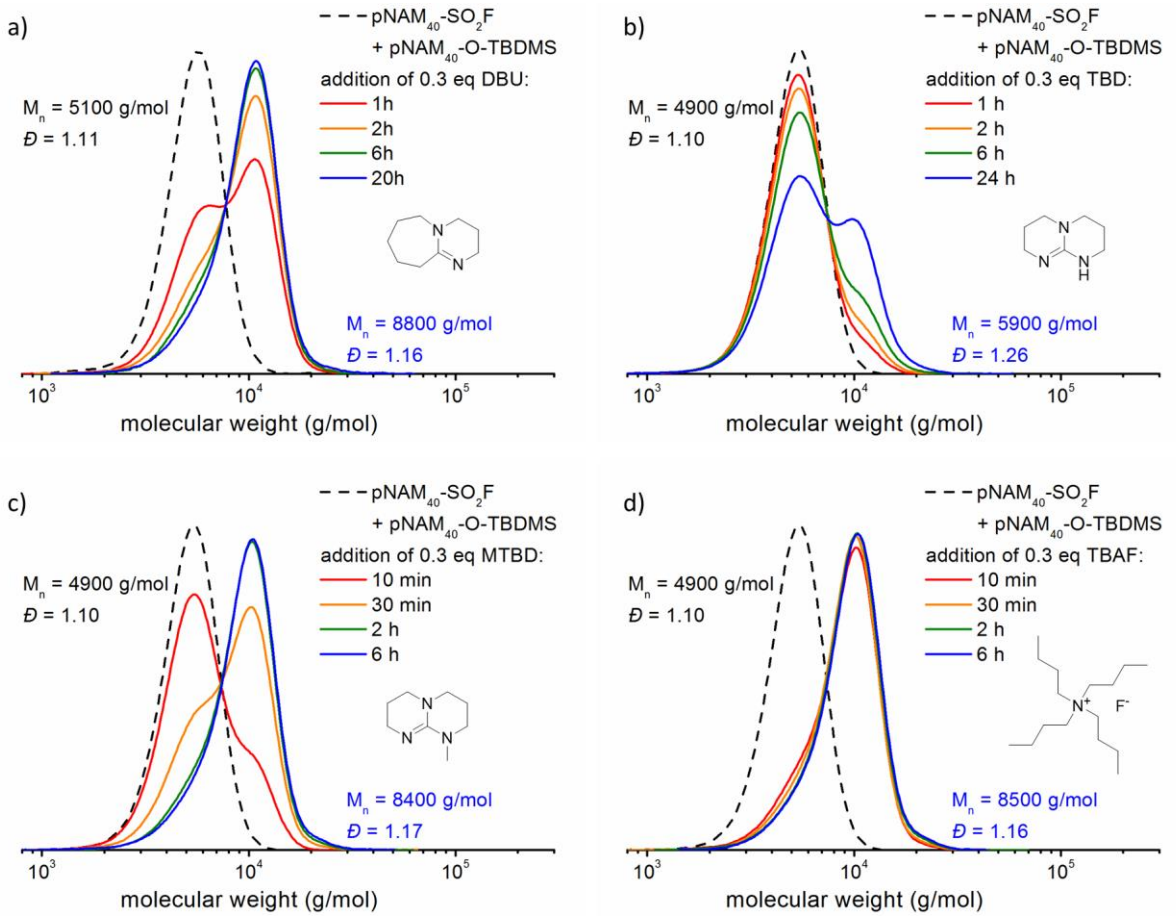


Figure 5). From the number distribution plot (Figure S7-S10) the coupling efficiency is calculated by deconvolution of the SEC traces. More details on the polymers before and after the coupling are summarized in Table S1.

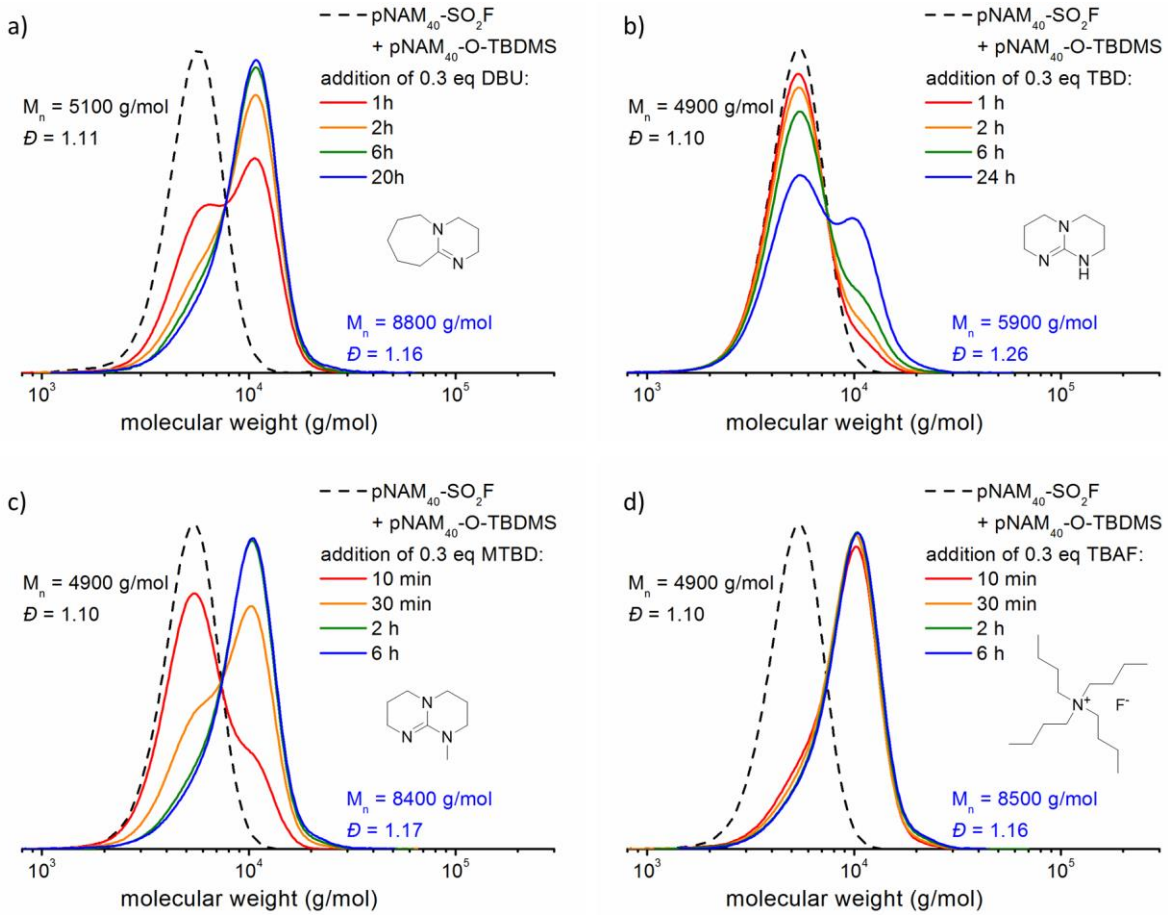


Figure 5. DMF-SEC traces of the precursor mixture (dashed) and the coupling reaction of pNAM-SO_2F and pNAM-O-TBDMS catalyzed by 0.3 eq. of either DBU (a), TBD (b), MTBD (c), or TBAF (d).

Using DBU, the polymer-polymer coupling proceeds to an excellent conversion (93 %) within 6 h (**Figure 5a**). The guanidine base TBD, which has previously been reported to be an efficient and cheap alternative,[22] does catalyze the SuFEx reaction, as evidenced by the appearance of a high molar mass population, but does not yield high conversions (60 % after 24 h) within the timeframe studied (**Figure 5b**). A possible side reaction might be the nucleophilic attack of the free amine of TBD with the CTA end-group.[44] Therefore, we tested the methylated analogue MTBD, which is less nucleophilic. In this case the polymer-polymer coupling reaction is extremely effective, yielding near-quantitative (92 %) coupling after 2 h (**Figure 5c**), which is considerably faster than DBU and verifies the activity of guanidine-based catalysts. We also tested TBAF as an alternative fluoride based catalyst to CsF. With addition of 0.3 equivalents of TBAF, the coupling reaction proceeded rapidly and yielded near-quantitative coupling within 10 min (**Figure 5d**). Surprised by such a fast reaction in comparison to the bases employed we decided to reduce the amount of catalyst to 0.1 eq

(Figure S11). Again, the coupling reaction proceeded to near-quantitative yields (94 % within only 30 min, deconvolution of number distribution plot is given in the SI, Figure S12). Such an efficient catalysis was only reported for the comparatively expensive superbase BEMP (pK_a = 27.6).[45] For comparison, this superbase was also examined as catalyst (Figure S11 b). As expected rapid and efficient coupling was observed within 30 min using 0.1 equivalents (93 %, deconvolution of number distribution plot is given in the SI, Figure S13). Nonetheless, the coupling reaction appears to proceed at a lower rate compared to TBAF (0.1 equivalents) considering the sample taken after 10 min. It is noteworthy to mention that anhydrous fluoride ions can have a very high pKa of 33.[46] However, in our case the TBAF trihydrate was employed, which has only a moderate basicity and hardly affects other functional groups.

- Variation of solvents

A limitation of all SuFEx reactions is the need for very polar and potentially harmful solvents, such as DMF or NMP. This aspect might limit the applicability and the range of polymers or other materials used for coupling. Based on the promising results using TBAF we altered the solvent for the coupling reaction. Considering that a certain amount of water was tolerated using the TBAF trihydrate as catalyst the reaction was tested in an aqueous environment (**Figure 6**).

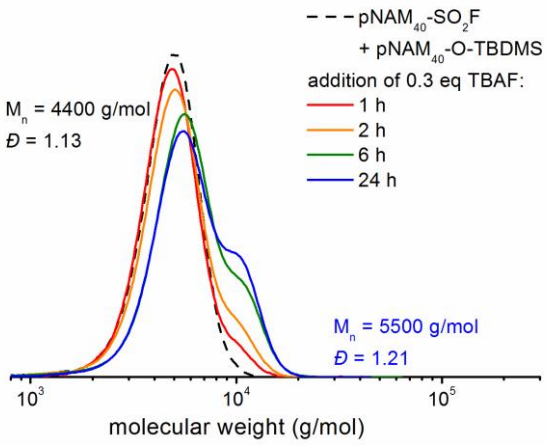


Figure 6. DMF-SEC traces of the precursor mixture (dashed) and the coupling reaction of pNAM-SO_2F and pNAM-O-TBDMS in aqueous solution catalyzed by 0.3 eq. of TBAF.

Even after 24 h only a low coupling efficiency of 44 % was observed (deconvolution of number distribution plot is given in the SI, Figure S14), and following the coupling over time

indicates a quantitative reaction would not be achieved within any feasible timeframe. Nonetheless, the reaction does work to some extent. It may be assumed that the fluoride ion is still capable of removing the TBDMS group, but certain basicity is still required in the system to preserve the deprotonated state of the released phenolate group, which can subsequently react with the sulfonyl fluoride.

An excellent solvent, which is often used for RAFT polymerizations and has no apparent toxicity, is 1,4-Dioxane. The coupling reaction was tested in this medium using DBU and TBAF as catalyst (**Figure 7**).

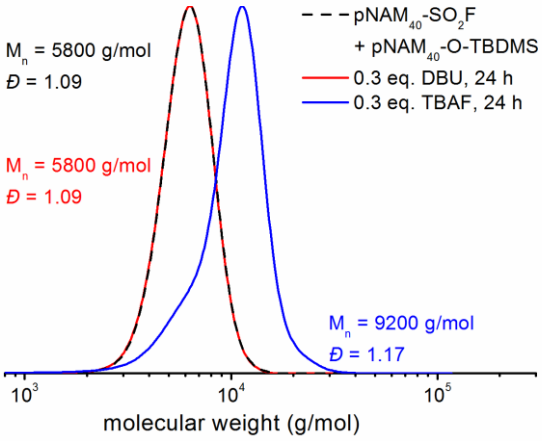


Figure 7. Normalized DMF-SEC traces of the precursor mixture (dashed) and the coupling reaction of pNAM-SO_2F and pNAM-O-TBDMS in 1,4-Dioxane. The reactions were catalyzed either by 0.3 eq. of DBU (red solid) or TBAF (blue solid).

Whilst no appreciable change was observed in the DMF-SEC following addition of DBU (red trace) indicating no polymer-polymer coupling, the reaction with TBAF (blue trace) yielded a high conversion (88 % after 24 h, deconvolution of number distribution plot is given in the SI, Figure S15). This result demonstrates that the fluoride ion and the resulting phenolate are accessible for reaction even in less polar solvents.

- Application of different polymers

Following the initial tests on the stability of the SuFEx-functional end-groups and the reactivity of various catalysts, the best conditions for coupling (DMF as solvent, TBAF as

catalyst) were applied to couple different types of polymers. Having demonstrated the well-controlled RAFT polymerization of styrene and *tert*-butyl acrylate (*t*-BA) we chose the resulting polymers as models for the SuFEx polymer-polymer coupling reaction. First, for both polymers homocouplings were examined using a 50/50 mixture of the two CTAs (

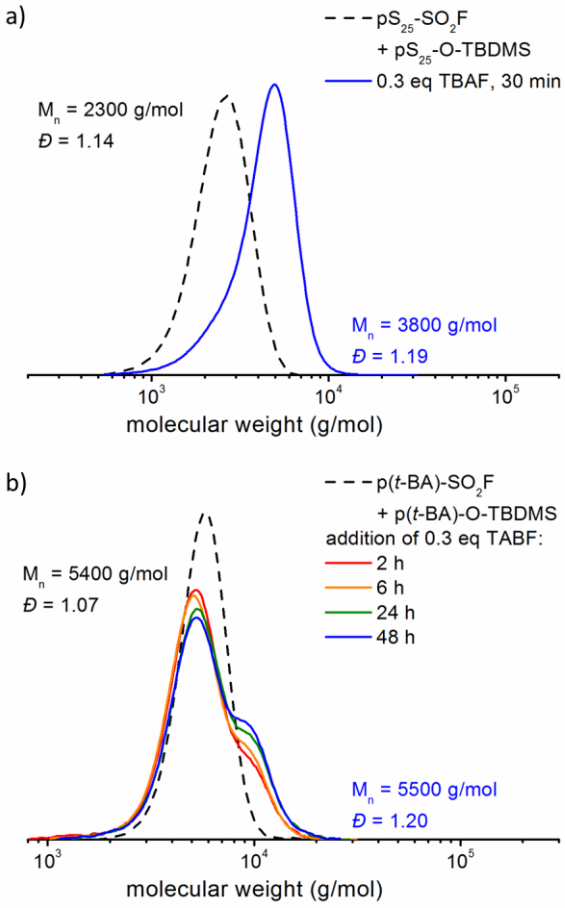


Figure). It is worth stressing that no purification procedures were applied in order to guarantee the equimolarity of the added reaction partners.

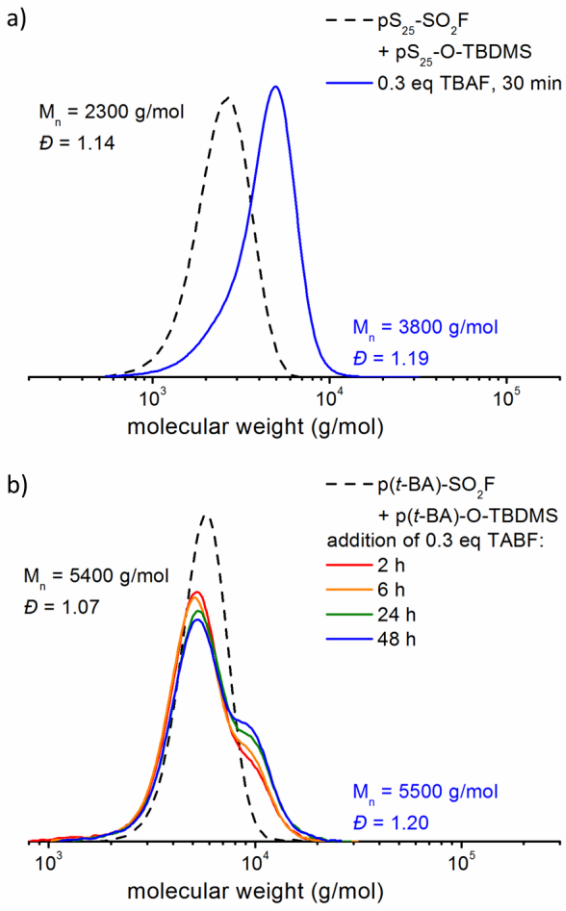


Figure 8. DMF-SEC traces of the precursor mixtures (dashed) and the coupling reaction of pS-SO_2F with pS-O-TBDMS (a) and p(*t*-BA)-SO_2F with p(*t*-BA)-O-TBDMS (b). In both cases 0.3 eq. of TBAF were added as a catalyst.

Although a high amount of monomer is still present (more than DMF added) the coupling reaction for pS proceeds rapidly to almost quantitative conversion (deconvolution of number distribution plot is given in the SI, Figure S16). No indication of side reactions were observed. In contrast p(*t*-BA) did not give quantitative coupling (32 % conversion after 48 h) and a significant amount of the precursor polymer(s) remain (deconvolution of number distribution plot is given in the SI, Figure S17).

In addition to the homocouplings, a pS-O-TBDMS and p(*t*-BA)-O-TBDMS were cross-coupled with pNAM-SO_2 to demonstrate the ability of the SuFEx reaction to prepare block copolymers from the crude polymerization media, requiring no purification or prior post-polymerization modification. The initial DMF-SEC traces of each homopolymer precursor

and the resulting block copolymers are given in

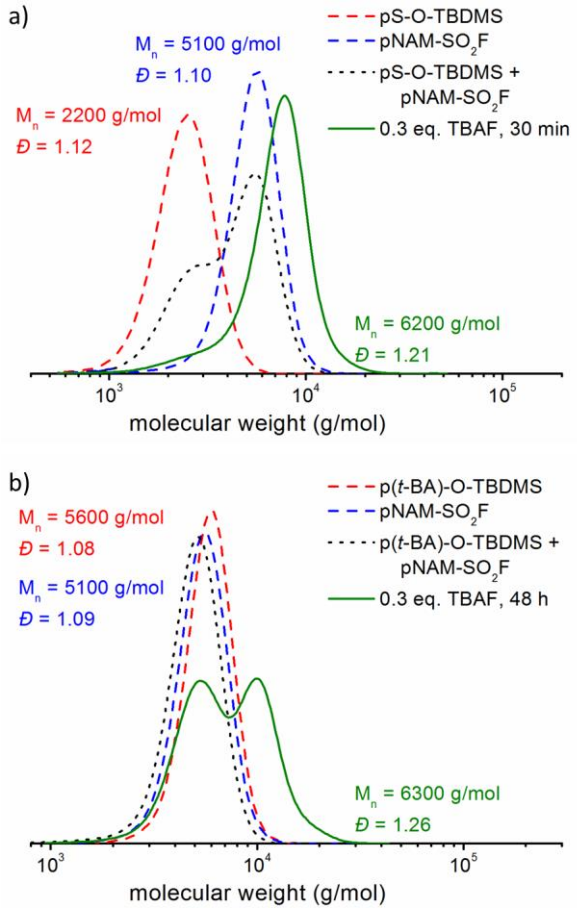


Figure.

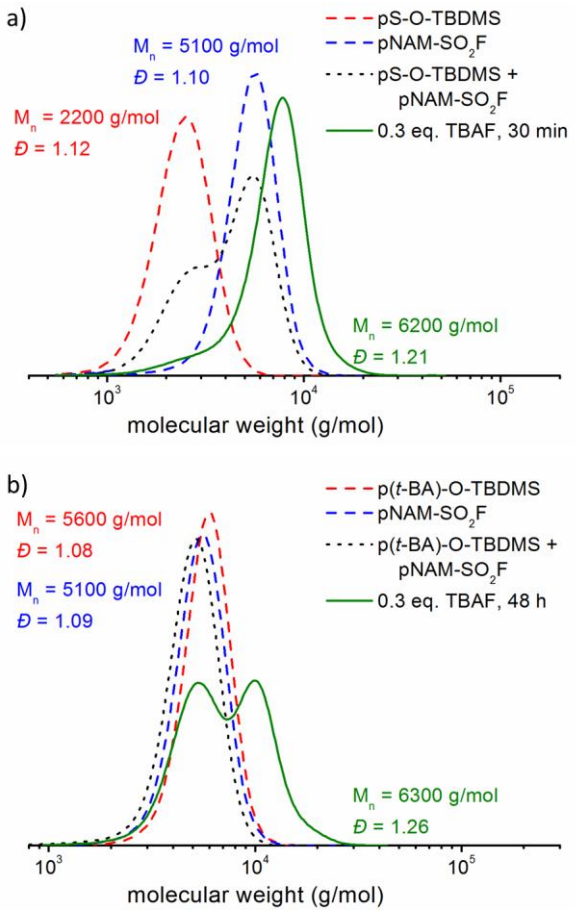


Figure 9. DMF-SEC traces of the individual precursors (dashed), their mixtures prior to addition of catalyst (dotted), and the coupling reactions of pNAM-SO_2F and pS-O-TBDMS (solid) (a), as well as pNAM-SO_2F and p(*t*-BA)-O-TBDMS (solid) (b). In both cases 0.3 eq. of TBAF were added as a catalyst.

As with the previous homocoupling reactions performed with p(*t*-BA) the cross-coupling was not high, with a significant amount of the precursor homopolymers remaining in the reaction solution. Possible explanations for this low yield is the hydrolysis of the *t*-BA to carboxylic acid that may deactivate the SuFEx reaction catalyst, or a possible Michael addition of the phenolate to the double bond of residual monomer, which is enhanced in the case of acrylate monomers in comparison to styrene or acrylamides. Further studies to clarify the mechanism of this reaction are currently on-going. However promisingly, the cross-coupling of pNAM-SO_2F with pS-O-TBDMS did show a fast and near-quantitative coupling within 30 min (similar in rapidity to the pure homocouplings). DMF-SEC of the solution post-coupling does show a small amount of low molar mass tailing which is likely due to a slight deviation from equimolarity when mixing the crude polymer solutions (excess of pS-O-TBDMS).

Conclusions

SuFEx and RAFT represent the first example for ideally orthogonal and efficient chemistry in polymer chemistry. The chain transfer agents bearing the required sulfonyl fluoride can be obtained in a single reaction step from commercial starting materials. Furthermore, this CTA 4-(fluorosulfonyl)benzyl butyl trithiocarbonate (FSBBTC) is capable of controlling the polymerisation of acrylate, acrylamide, and styrenic monomers to obtain well-defined polymers with no apparent side reaction. Both the silane and the sulfonyl fluoride group remain intact and active following polymerisation involving reactive radicals and elevated temperatures, and the coupling reaction is only instigated by the introduction of a suitable trigger (catalyst), which may then proceed smoothly and rapidly to high conversions. Sterically hindered, strong bases such as DBU or MTBD are suitable candidates to trigger the SuFEx reaction, however we have demonstrated excellent polymer-polymer coupling efficiency using tetrabutyl ammonium fluoride (TBAF), which yields near-quantitative polymer coupling in less than an hour and works well in less polar solvents than the commonly employed DMF or NMP. In addition, in contrast to the well-known SuFEx catalyst CsF, TBAF is well-soluble in various organic solvents and shows high dissociation constants making the fluoride ion accessible for reactions. The reaction mechanism, however, cannot be the same as assumed for the base mediated reaction. In the case of TBAF, the reaction must be initiated by a release of the phenolate which subsequently reacts with the sulfonyl fluoride. While traces of water are tolerated, an aqueous environment decreases the yield of the reaction considerably, but does not fully prevent the reaction. We assume that the basicity of the environment or the deprotonation of the phenolic alcohol, respectively, is a key prerequisite for an efficient reaction. However, further studies are necessary to fully elucidate this mechanism.

Finally we compared the reactivity of the coupling reaction with different types of polymers using pS, pNAM and p(*t*-BA) to represent the styrenic, acrylamido and acrylate monomer families, respectively. Both polystyrene and the acrylamido polymer pNAM showed excellent coupling efficiencies even in cross-coupling experiments. However, the acrylate p(*t*-BA) did not yield a quantitative coupling in either homocoupling or cross-coupling reactions with pNAM. It is important to note that, to illustrate the versatility for the reaction, all polymers were used from their crude polymerisation mixtures without purification. Therefore residual initiator and especially monomer were not excluded from the reaction. A potential side reaction might be the Michael addition of the phenolate to the double bond

which is enhanced in the case of acrylate monomers in comparison to styrene or acrylamides. Studies to elucidate potential side reactions and conditions to minimize them are currently on-going. Nevertheless, for the first time we demonstrated that two different types of polymers could quantitatively be coupled within minutes, and without additional modification or stringent purification steps. Therefore, this work demonstrates that SuFEx chemistry can conveniently be combined with controlled radical polymerisations and fully tolerates the conditions applied in a living radical polymerisation. The orthogonality of these two techniques makes their combination a novel and powerful tool in polymer science that is capable to create a variety of functional materials.

Experimental

- Materials

All reagents, monomers, deuterated solvents for NMR and aluminum oxide were purchased from Sigma-Aldrich, if not stated otherwise. Stabilizers were removed by passing the monomers through a short aluminum oxide column. Dimethyl 2,2'-azobis(2-methylpropionate) (V-601) was purchased from Wako Specialty Chemicals. All solvents were bought from commercial sources and used as received. The catalysts 1,8-Diazabicycloundec-7-ene (DBU), 1,3,5-Triazabicyclo[4.4.0]dec-5-ene (TBD), 7-Methyl-1,5,7-triazabicyclo[4.4.0]dec-5-ene (MTBD), and 2-*tert*-Butylimino-2-diethylamino-1,3-dimethylperhydro-1,3,2-diazaphosphorine (BEMP) were bought from Sigma-Aldrich used as received. Tetrabutylammonium fluoride (TBAF) was ordered as a 1.0 M solution in THF. 4-(Bromomethyl)benzene-1-sulfonyl fluoride, the bifunctional linker ((propane-2,2-diylbis(4,1-phenylene))bis(oxy))bis(tert-butyldimethylsilane) (TBDMS Bisphenol A), and 2-propionic acidyl butyl trithiocarbonate (PABTC) were synthesised according to previously published procedures.[20, 21, 34]

- Characterization

NMR spectra were recorded on Bruker DPX-300, DPX-400 and HD-700 instruments. Size exclusion chromatography (SEC) measurements were performed on an Agilent PL50 equipped with 2 Agilent Polargel Medium Columns eluting with dimethylformamide containing 0.1 M LiBr as an additive at 50 °C. The flow rate was 1 mL/min and detection was achieved using simultaneous refractive index (RI) and UV (λ = 280 nm) detectors. As

alternative an Agilent 1260 GPC-MDS fitted with differential refractive index (DRI), light scattering (LS), and viscometry (VS) detectors equipped with 2 × PLgel 5 mm mixed-D columns (300 × 7.5 mm), 1 × PLgel 5 mm guard column (50 × 7.5 mm) was used with the mobile phase being chloroform with 2% triethylamine at a flow rate of 1.0 mL/min. All molecular weights were calculated relative to narrow PMMA standards and every sample was passed through 0.2 µm PTFE filter before analysis.

- Synthesis of CTAs

4-(fluorosulfonyl)benzyl butyl trithiocarbonate. A 20 % w/w aqueous sodium hydroxide solution (0.89 g, 0.18 g of NaOH, 4.4 mmol) was added to a stirred mixture of butanethiol (0.4 g, 0.48 mL, 1 eq. 4.4 mmol) in Acetone (1 mL). The resulting clear solution was stirred for 30 min at room temperature. After the addition of carbon disulfide (0.37 g, 1.1 eq., 4.9 mmol) and another 30 min of stirring, the resulting orange solution was cooled to approximately 10 °C. 4-(Bromomethyl)benzene-1-sulfonyl fluoride (1.12 g, 1 eq., 4.4 mmol) was slowly added and the reaction mixture was stirred for another 60 min. Diethyl ether (50 ml) was added and the organic phase was washed twice with a saturated sodium hydrogen carbonate solution and water. After drying over magnesium sulfate and removal of the solvent under reduced pressure the crude product was purified by flash chromatography using a mixture of hexane/ethyl acetate (gradient from 0% to 30% Ethyl Acetate) as eluent. Yield: 80 % (1.2 g, 3.5 mmol). ^{1}H-NMR ($CDCl_3$, 300 MHz, pm): δ = 7.96 (m, 2H, aromatic CH), 7.62 (m, 2H, aromatic CH), 4.71 (s, 2H, -Bz-CH_2-S-), 3.40 (t, 2H, *J* = 7.35 Hz, -S-CH_2-CH_2-CH_2-CH_3), 1.71 (m, 2H, -S-CH_2-CH_2-CH_2-CH_3), 1.45 (m, 2H, -S-CH_2-CH_2-CH_2-CH_3), 0.95 (t, 3H, *J* = 7.27 Hz, -S-CH_2-CH_2-CH_2-CH_3). ^{13}C-NMR ($CDCl_3$, 300 MHz, pm):): δ = 130.3, 128.7, 39.7, 37.2, 29.9, 22.1, 13.6. HRMS (ESI): $[M+Na]^+$ calculated: 360.9831, found: $[M+Na]^+$ 360.9829.

4-((tert-butyldimethylsilyl)oxy)phenyl 2-(((butylthio)carbonothioyl)thio)-propanoate. 2-propionic acidyl butyl trithiocarbonate (0.50 g, 2.1 mmol), 4-(*tert*-butyldimethylsiloxy)phenol (0.49 g, 1.05 eq. 2.2 mmol), and 4-(dimethylamino)pyridine (DMAP) (0.03 g, 0.1 eq. 0.2 mmol) were dissolved in dry DCM (10 ml) and N-(3-Dimethylaminopropyl)-N′-ethylcarbodiimide hydrochloride (EDC) (0.44 g, 1.1 eq. 2.3 mmol) was added in small portions. After stirring for 16 h at room temperature, the mixture was diluted with diethyl ether (50 ml) and the organic phase was washed once with a 0.5 M HCl solution, twice with a saturated sodium hydrogen carbonate solution and once with water.

After drying over magnesium sulfate and removal of the solvent under reduced pressure the crude product was purified by flash chromatography using a mixture of hexane/ethyl acetate (gradient from 0 % to 50 % Ethyl Acetate) as eluent. Yield: 75 % (0.7 g, 1.6 mmol). ^{1}H-NMR ($CDCl_3$, 300 MHz, pm): δ = 6.94 (m, 2H, aromatic CH), 6.83 (m, 2H, aromatic CH), 4.98 (q, 1H, *J* = 7.35 Hz, -OOC-C(CH_3)*H*-S-), 3.40 (t, 2H, *J* = 7.44 Hz, -S-C*H*$_2$-CH_2-CH_2-CH_3), 1.78-1.65 (m, 5H, -OOC-C(C*H*$_3$)H-S-, -S-CH_2-C*H*$_2$-CH_2-CH_3), 1.45 (m, 2H, -S-CH_2-CH_2-C*H*$_2$-CH_3), 1.01-0.92 (m, 12H, Si-C(CH_3)$_2$-C(C*H*$_3$)$_3$, -S-CH_2-CH_2-CH_2-C*H*$_3$), 0.19 (m, 6H, Si-C(C*H*$_3$)$_2$-C(CH_3)$_3$). ^{13}C-NMR ($CDCl_3$, 300 MHz, pm): δ = 222.0, 122.0, 120.6, 47.9, 37.1, 29.9, 25.7, 22.1, 16.6, 13.6, -4.5.

- Polymerizations

Typical protocol: chain transfer agent (CTA), monomer, initiator (V-601) and DMF (except for styrene) were introduced into a vial equipped with a magnetic stirrer and sealed with a rubber septum. The solution was degassed with a constant stream of nitrogen for 10 min, the flask was then put in a thermostated oil bath set at 65 °C. The polymerizations were stopped by cooling the flask and opening it to air. Conditions specific to each polymerization are detailed in **Table 1**. Conversions were determined by ^{1}H-NMR by comparison of the integration of the vinyl protons corresponding to the remaining monomer with the integration of polymer side chains signals. The final concentration (in mg/g solution) of CTA was determined gravimetrically weighing the empty vial with stirrer and subtracting this weight from the final mass of the vial with solution.

Table 1. Summary of experimental conditions for polymerizations.

Monomer	Solvent	CTA	$[M]_0$ (mol/L)	$[M]_0$/[CTA]	[CTA]/$[I]_0$	Time (h)
NAM	DMF	FSBBTC	3	40	20	4
Styrene [a]	-	FSBBTC	7.6 [d]	70	10	8
MMA	DMF	FSBBTC	3	60	20	4
NAM [b]	DMF	Mixed [c]	3	40	20	4
Styrene [a]	-	Mixed [c]	7.6 [d]	100	20	6
t-BA	DMF	Mixed [c]	3	40	20	4
Styrene [a]	-	TBDMSPh-PABTC	7.6 [d]	100	20	6
t-BA	DMF	TBDMSPh-PABTC	3	40	20	4

[a] These polymerizations were done at 70 °C; [b] Five different batches were prepared with these conditions; [c] 1/1 mixture of the CTAs FSBBTC and TBDMSPh-PABTC; [d] polymerization in bulk conditions.

- Coupling reactions

Using the bifunctional linker TBDMS Bisphenol A: Exactly 0.5 eq. of TBDMS Bisphenol A (stock solution in DMF) were added directly to the solution obtained after polymerization. To start the reaction 0.3 eq. DBU (stock solution in DMF) were added and the mixture was stirred for 72 h at RT.

Mixed CTAs: The solutions obtained from the polymerization with both complementary CTAs (FSBBTC and TBDMSPh-PABTC) were used without further treatment. The coupling reaction was then initiated by the addition of the respective catalyst (DBU, TBD, MTBD, TBAF, or BEMP) as a stock solution in DMF.

Block copolymer formation: Exactly 1 eq. of each polymer, directly taken out of the polymerization solutions, were combined in a vial and thoroughly mixed. To start the coupling reaction 0.3 eq. TBAF (stock solution in DMF) were added and the mixture was agitated until no more changes in SEC traces were observed.

Associated content

Electronic supplementary information.

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